Photovoltaic System Design and Sizing

National Renewable Energy Laboratory
Golden, Colorado

www.nrel.gov

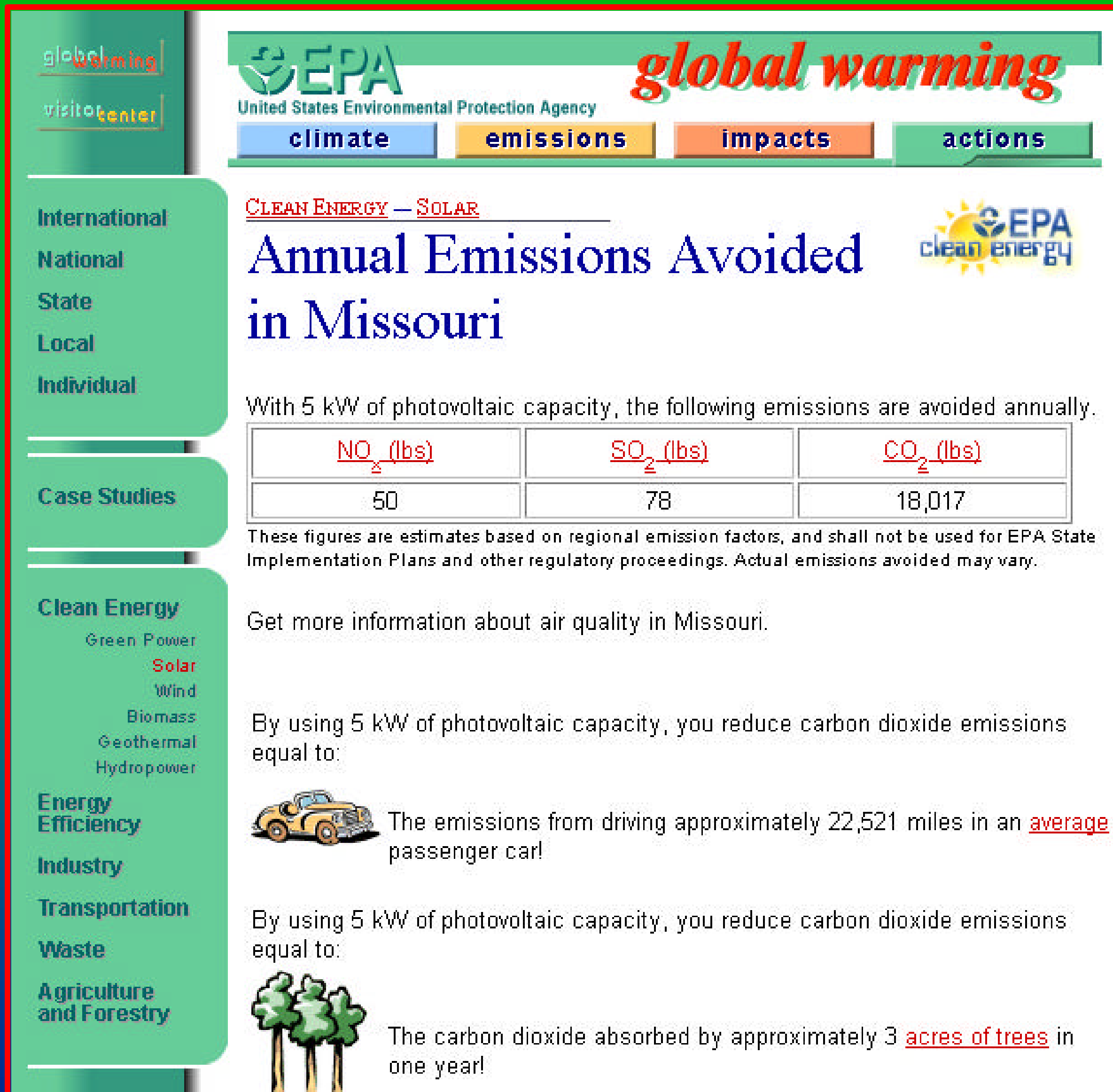
Photovoltaics, solar power, PV, or PVs, it's all the same — electric power from the sun.

One of the World's Best Kept Secrets — Photovoltaics!

- Exceeded $1 billion in sales in 1998; and $2 billion in 2000
- Annual sales growth of 20–30% for last five years
- Annual growth nearly twice that of U.S. PC market
- World demand exceeds world supply

Why Photovoltaics?

- PV is silent and generally aesthetically pleasing.
- PV has far fewer risks and environmental impacts than conventional sources of energy.
- PV produces no pollutants during operation, making it a preferred option for offsetting emissions that result from fossil fuel use.
- PV can become *net producers* of energy after only 3-4 years of operation.


global warming
visitor center

EPA United States Environmental Protection Agency

global warming

climate | emissions | impacts | actions

International
National
State
Local
Individual

Case Studies

Clean Energy
Green Power
Solar
Wind
Biomass
Geothermal
Hydropower
Energy Efficiency
Industry
Transportation
Waste
Agriculture and Forestry

CLEAN ENERGY — SOLAR

EPA clean energy

Annual Emissions Avoided in Missouri

With 5 kW of photovoltaic capacity, the following emissions are avoided annually.

NO_x (lbs)	SO_2 (lbs)	CO_2 (lbs)
50	78	18,017

These figures are estimates based on regional emission factors, and shall not be used for EPA State Implementation Plans and other regulatory proceedings. Actual emissions avoided may vary.

Get more information about air quality in Missouri.

By using 5 kW of photovoltaic capacity, you reduce carbon dioxide emissions equal to:

The emissions from driving approximately 22,521 miles in an average passenger car!

By using 5 kW of photovoltaic capacity, you reduce carbon dioxide emissions equal to:

The carbon dioxide absorbed by approximately 3 acres of trees in one year!

http://199.223.18.220/epa/rew/rew.nsf/solar/index.html

Blackout! It Can Happen To You.

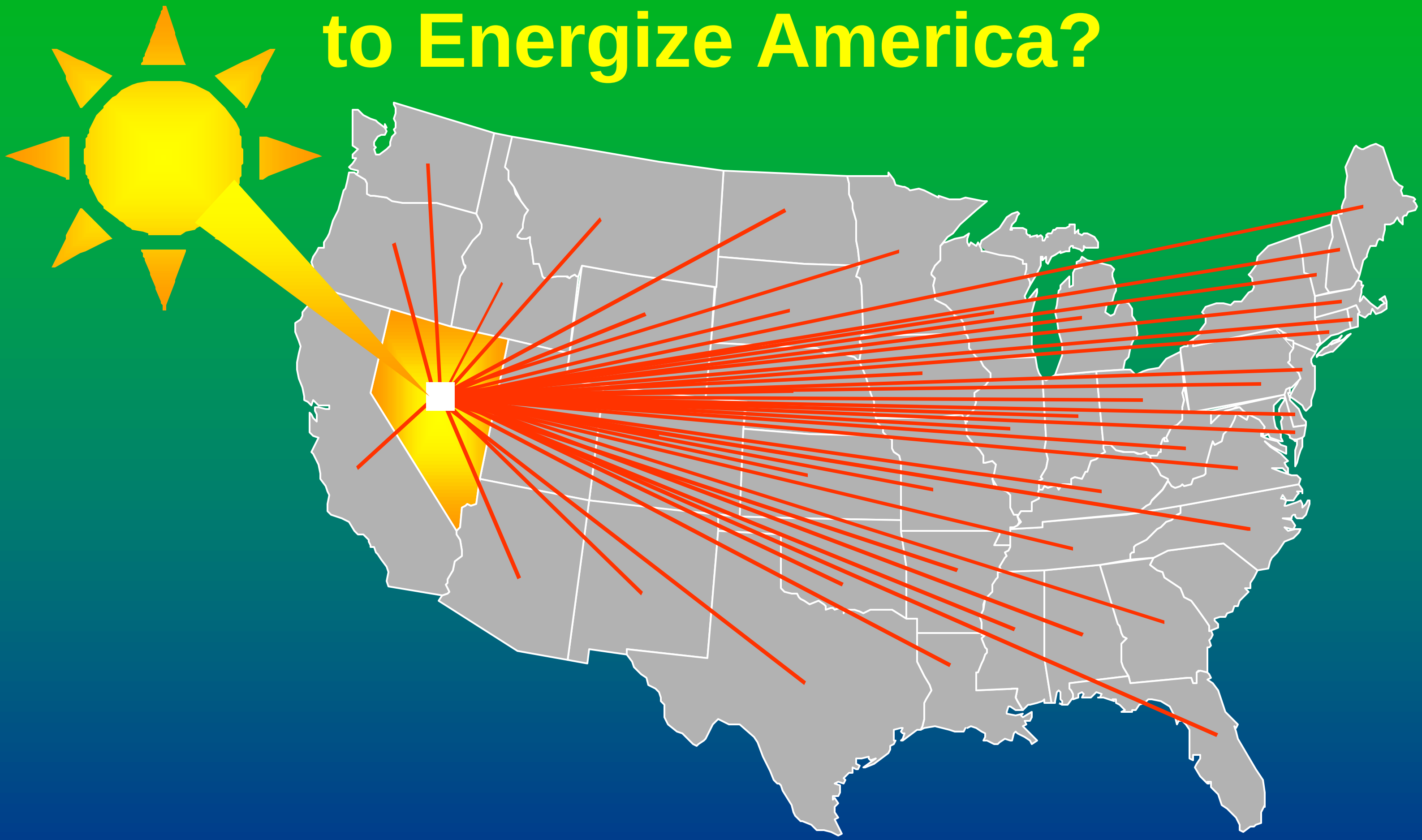
July 2, 1996

Before

After

Source: W. Becker, U.S. DOE

Is There Enough Sunshine to Energize America?



That's right! This bright spot covers a circle of Nevada desert about 100 miles across, that if covered with modern PV arrays, would satisfy America's entire electricity demand.

Our goal is to make you an educated, renewable energy-smart consumer.

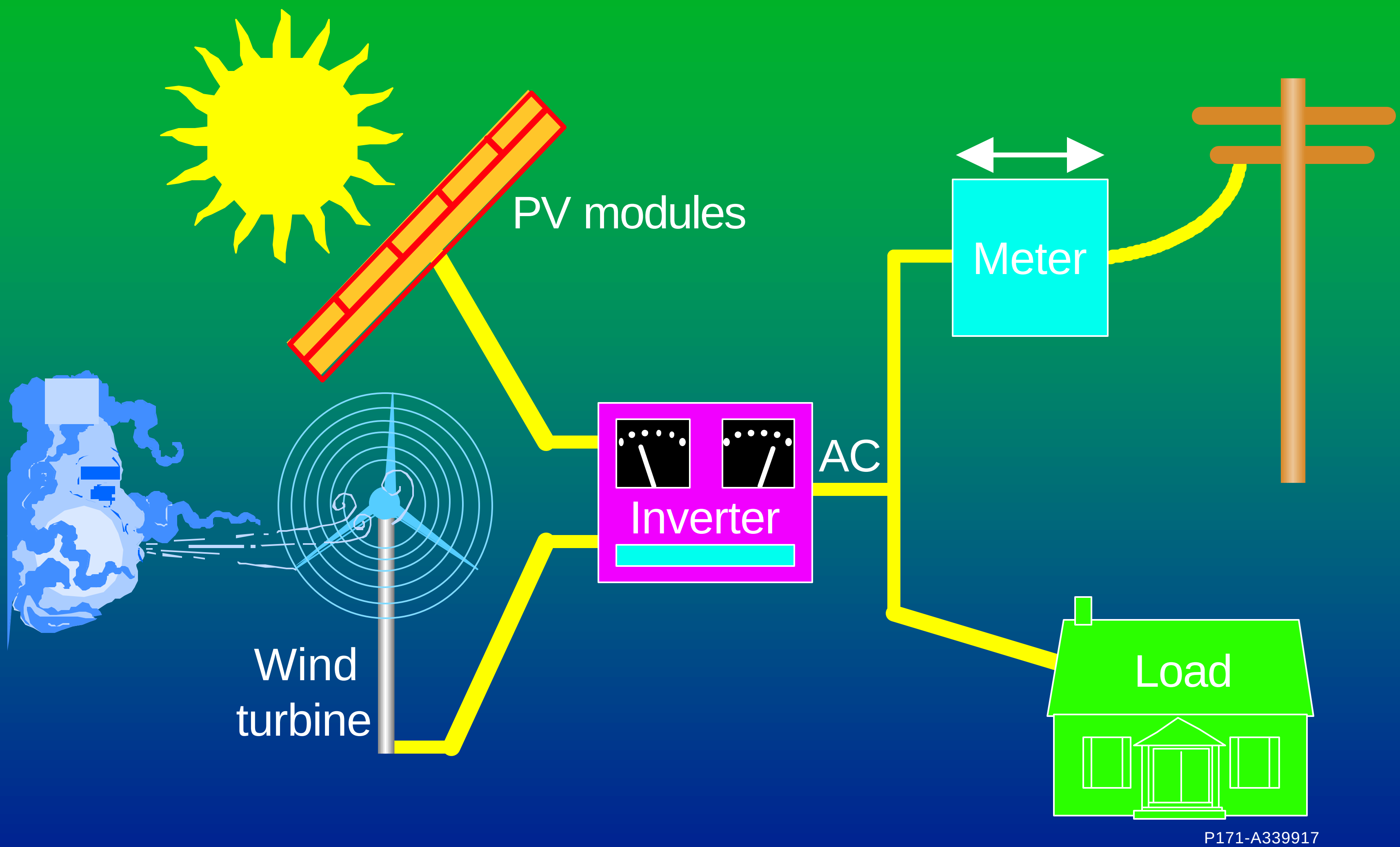
Outline

- Types of PV Systems
- System Design and Sizing Process
  - Energy Audit, Conservation and Energy Efficiency Measures, Solar Resource Determination, Design, Procurement, Installation, Commissioning, Maintain System and Monitor Performance
- Suggestions for Success

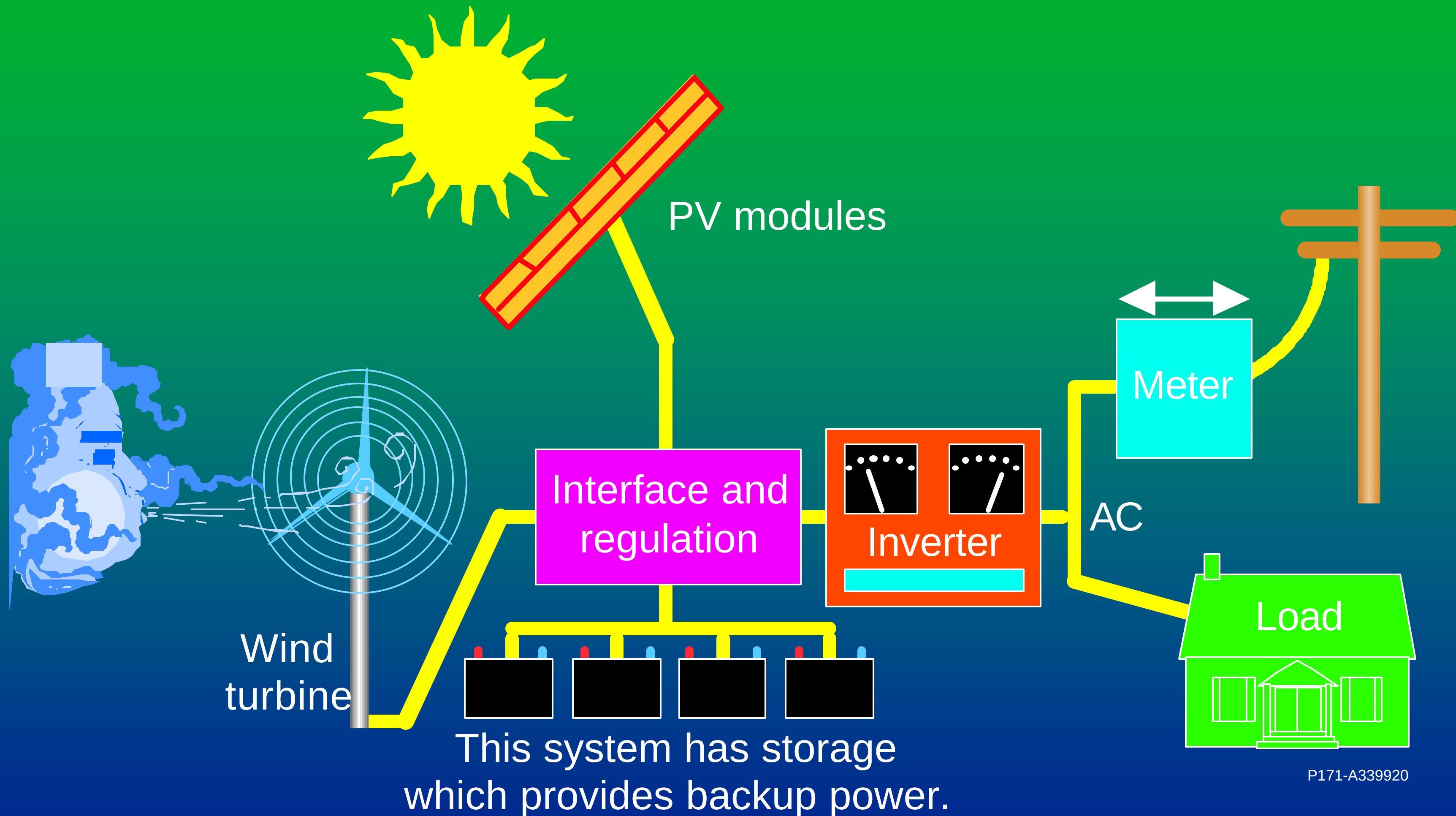
Types of PV Systems

- Grid-interconnected
  - no electrical energy storage
  - with full or emergency electrical energy storage
- Grid independent
  - no electrical energy storage
  - with electrical energy storage

On-Grid AC System without Storage



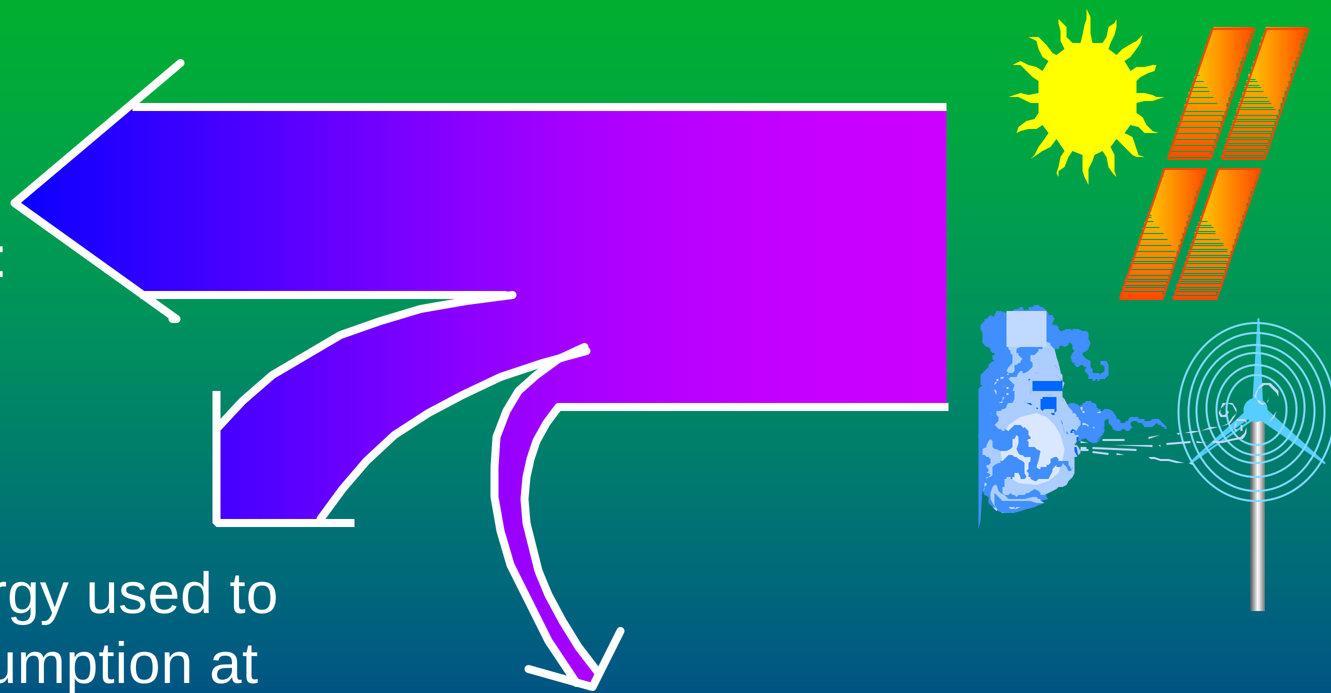
On-Grid AC System with Storage



Net metering — where electricity generated from renewable energy is used to offset consumption from your local utility.

Net Metering of Renewable Energy

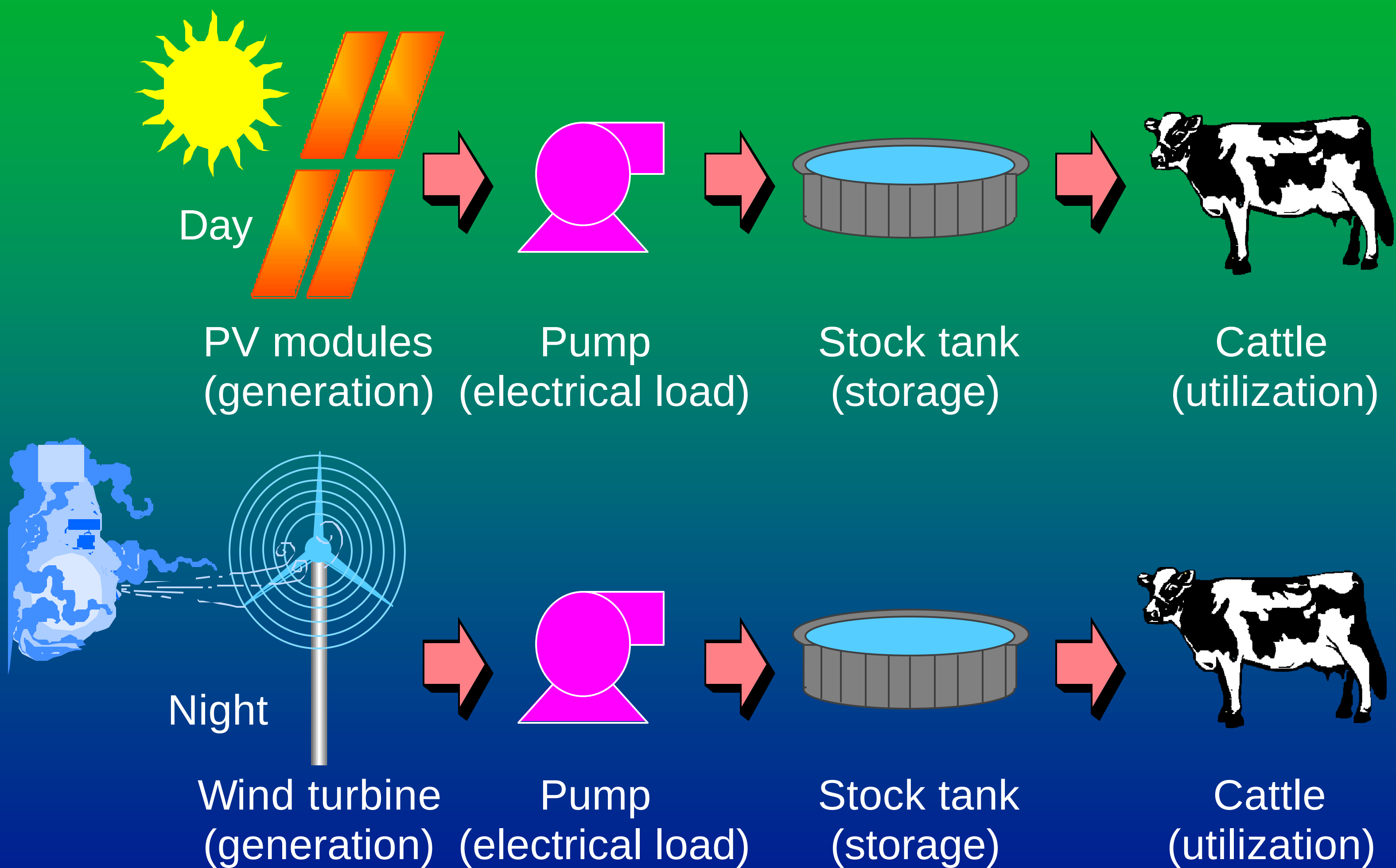
Energy consumed immediately: retail rate



Excess energy used to ***offset*** consumption at another time: retail rate

Net excess energy (determined monthly or annually): retail rate, avoided cost, or given to the utility

Off-grid RE System without Storage



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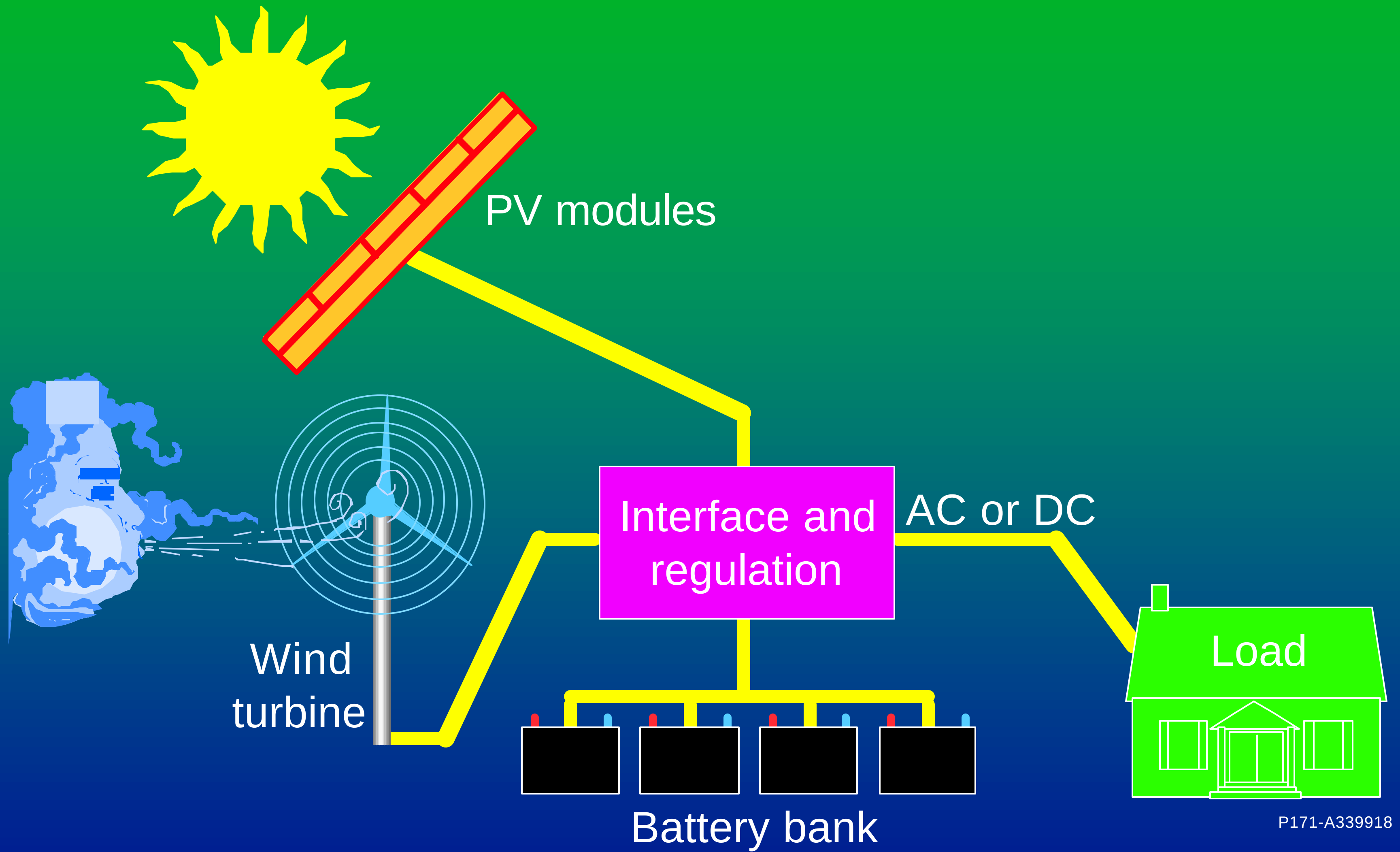
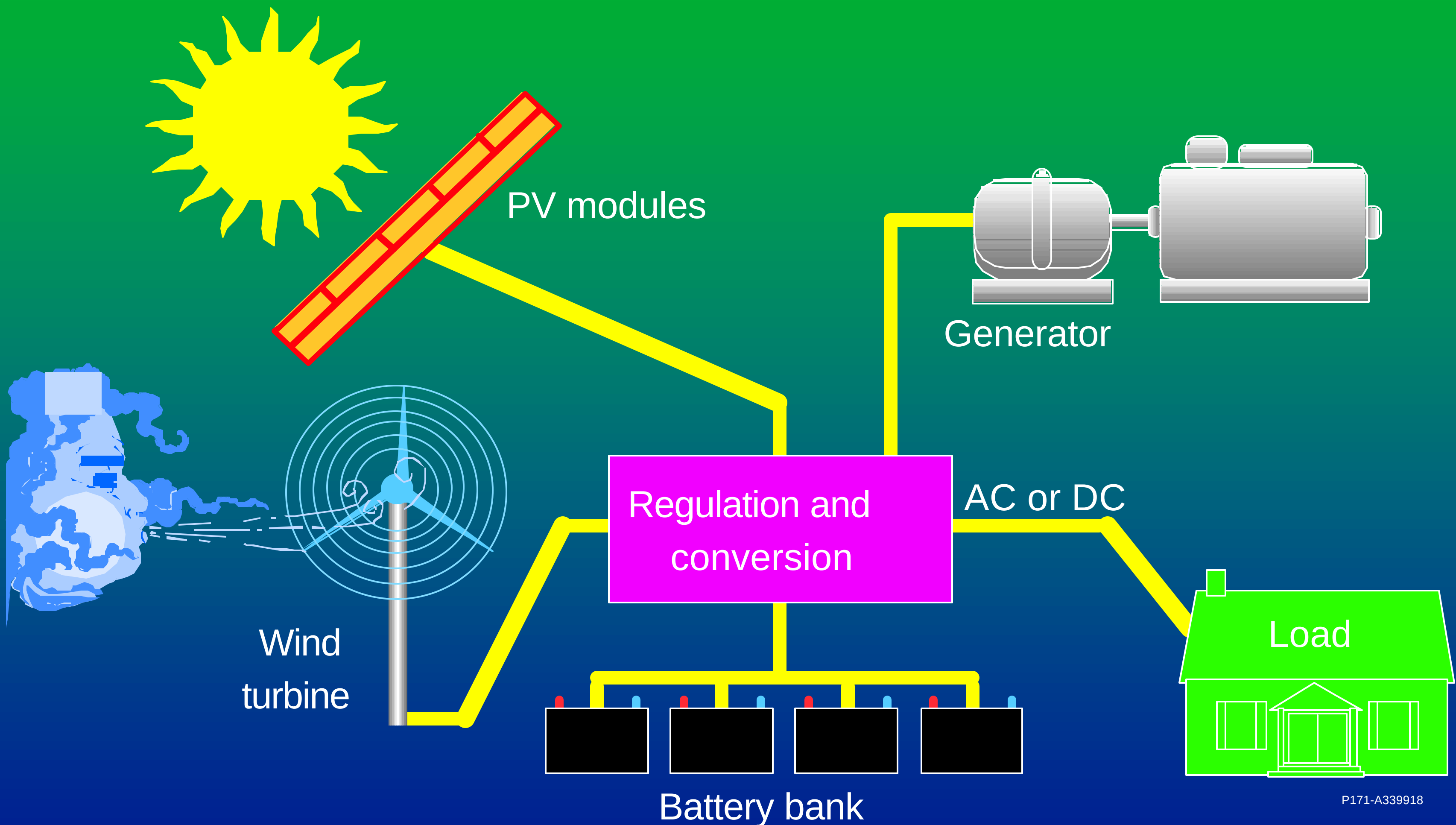
Off-Grid RE System with Storage



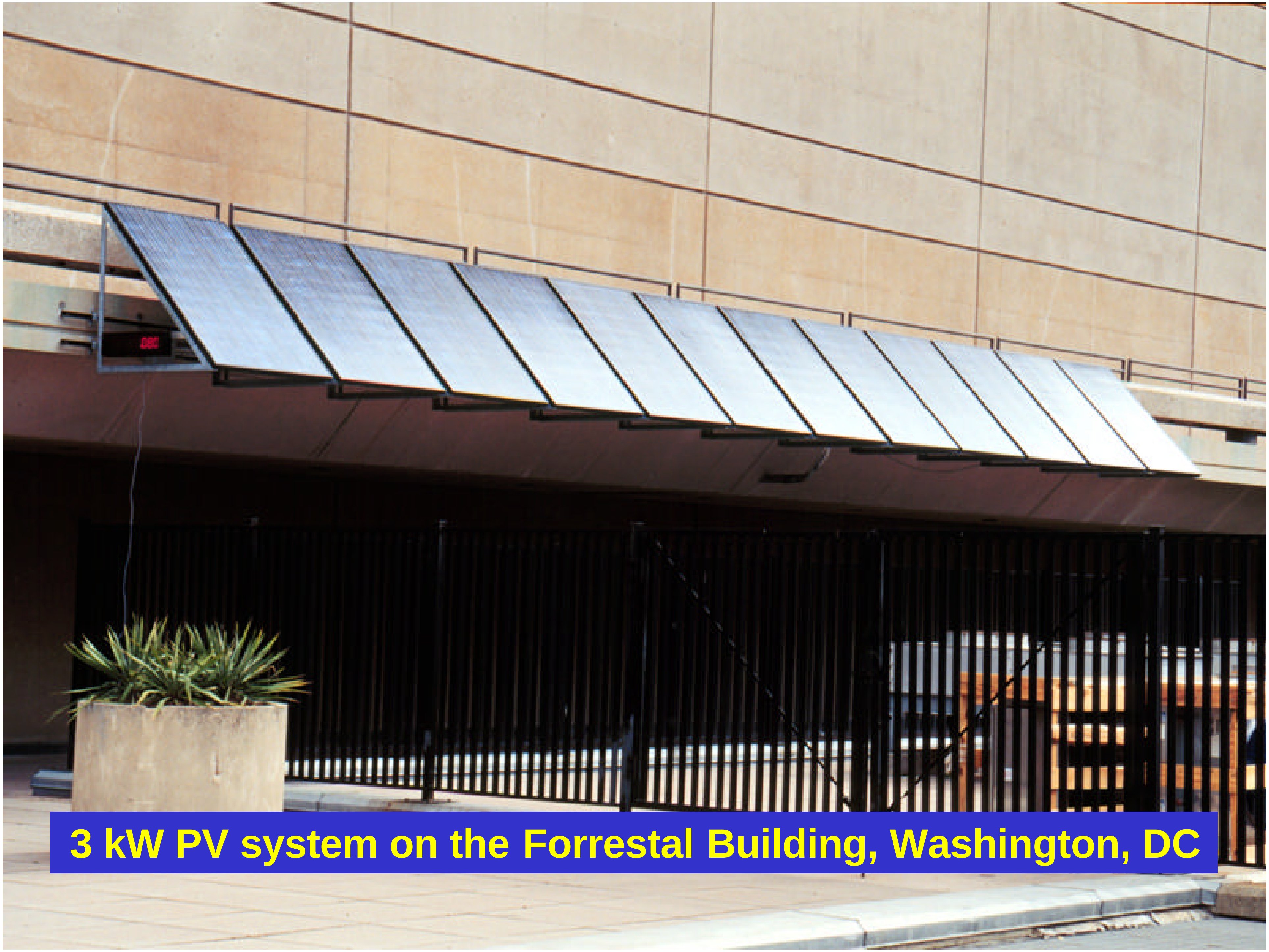
Hybrid Power Systems

Combine multiple sources to deliver reliable electric power



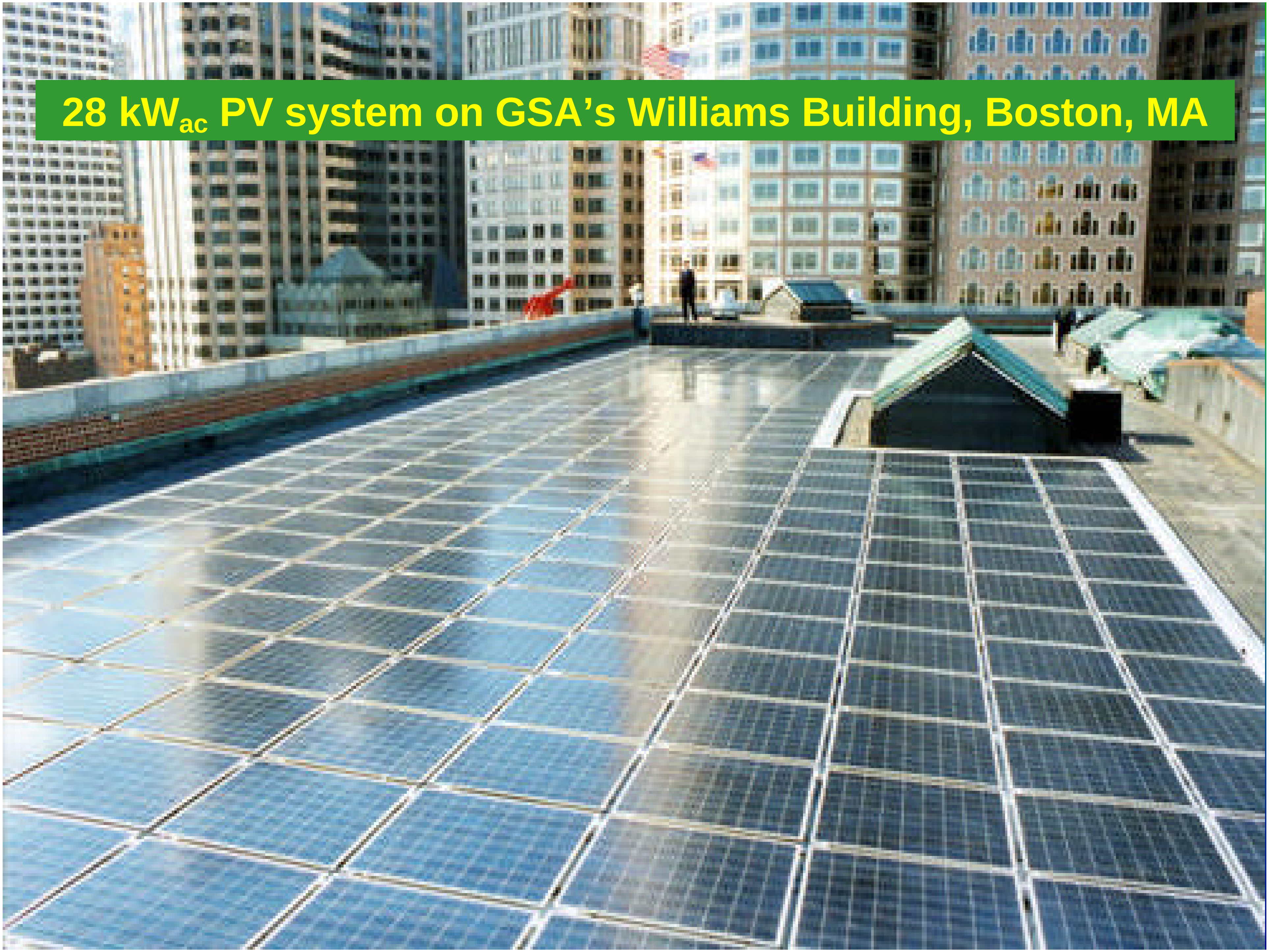

115 kW PV system at Dangling Rope Marina
in Utah's Glen Canyon National Recreation Area

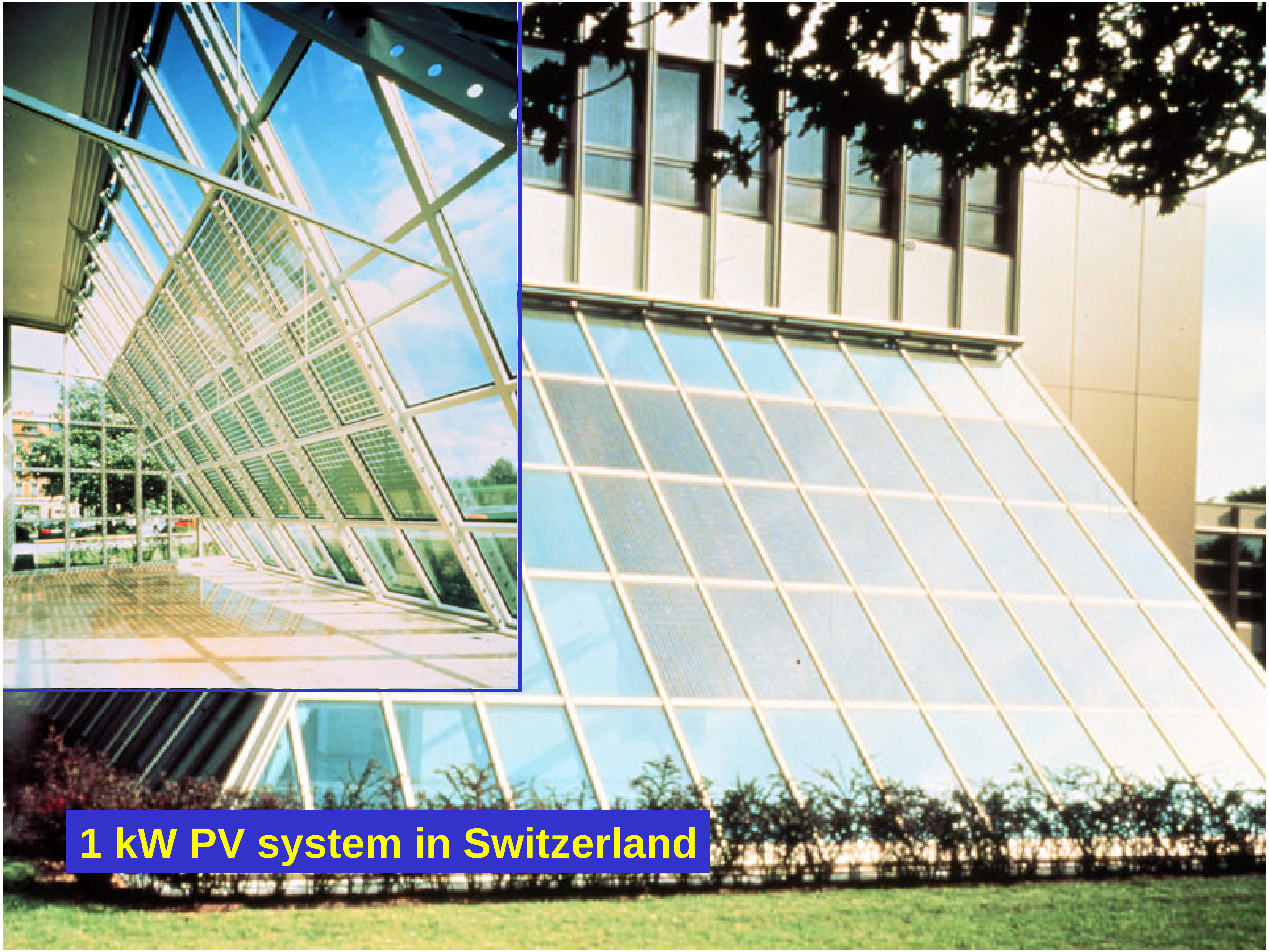

30 kW PV system at the Pentagon



3 kW PV system on the Forrestal Building, Washington, DC

28 kW_{ac} PV system on GSA's Williams Building, Boston, MA




1 kW PV system in Switzerland


1.5 kW$_{dc}$ PV system in Bowie, Maryland

Overview of Design and Sizing Process

- Perform an Electrical Energy Assessment
- Implement Conservation and Energy Efficiency Measures
- Determine the Solar Resource
- Design and Size the System
- Procure the System
- Install the System
- Commission the System
- Maintain System and Monitor Performance

Perform an Electrical Energy Assessment

- How much electricity are you using now?
  - Load profile by time of day
  - Energy usage by day and month
- What is the projected electrical load?
- Are there any special considerations?
  - Critical loads versus deferrable loads
  - Interconnection issues
  - Ownership issues

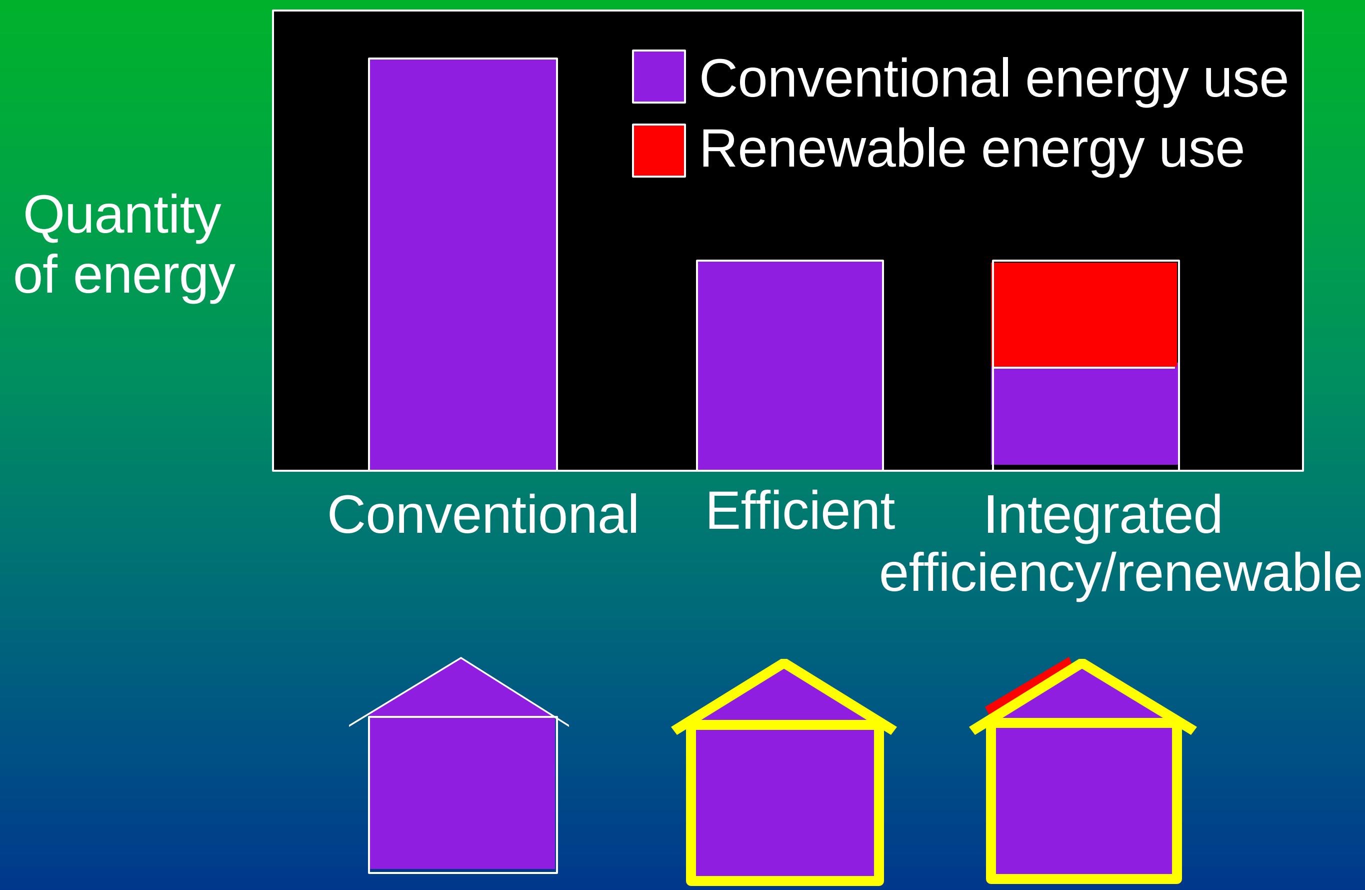
Implement conservation and energy efficiency measures

The result will be the most cost-effective PV system.

“Every watt not used is a watt that doesn’t have to be produced, processed, or stored.”

Richard Perez, Homepower Magazine

Relationship Between Efficiency/Renewables



Bundled measures achieve deeper savings

Renewables contribute to 30% reduction goal

One dollar spent on an energy efficient appliance will save three dollars on PV components.

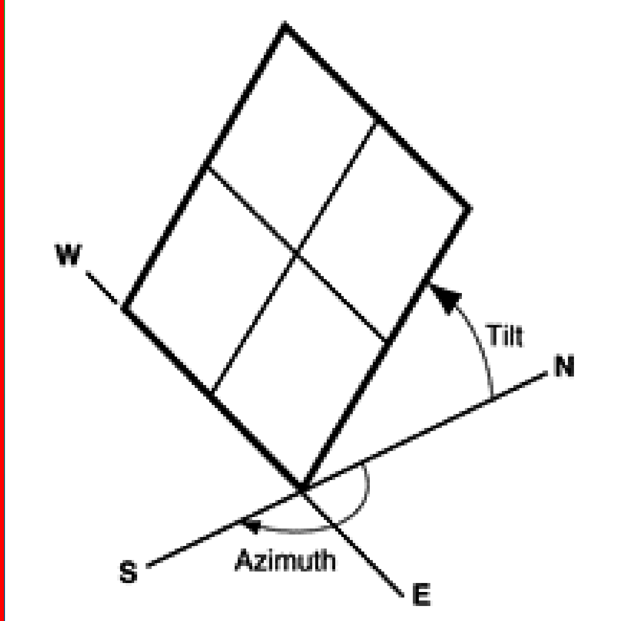
Richard Perez, 1991

How much PV is needed to run a vending machine?

This 1.8 kW PV system powers only the Coke machine.

Determine the Solar Resource

- Location
- Tilt
- Orientation
- Type of PV Mounting
  – Fixed or Tracking

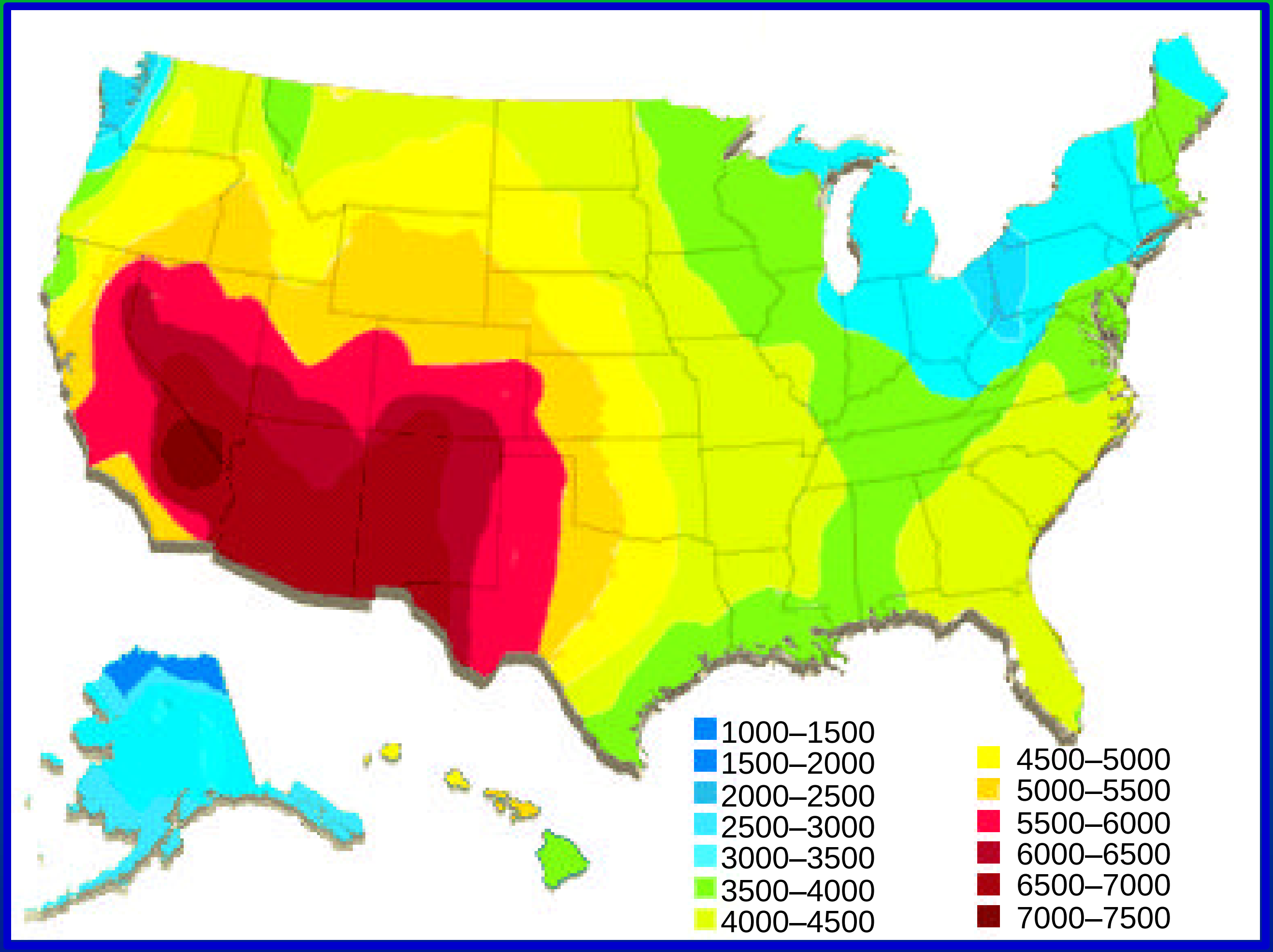


PV array facing south at fixed tilt.

- Check out:
  http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/sum2/

Average Annual Daily Solar Insolation

(Wh/m²/day)



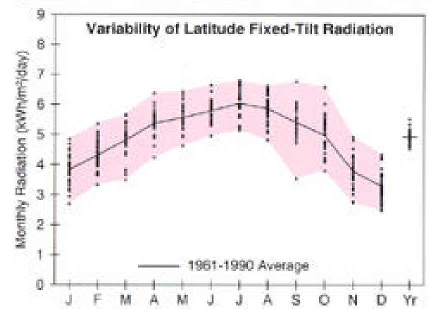
Solar Resource Data Sheet

Kansas City, MO

WBAN NO. 03947

LATITUDE: 39.30° N
LONGITUDE: 94.72° W
ELEVATION: 315 meters
MEAN PRESSURE: 984 millibars

STATION TYPE: Secondary



Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	2.2	3.0	3.9	5.1	5.9	6.5	6.6	5.8	4.6	3.6	2.3	1.9	4.3
	Min/Max	1.8/2.6	2.5/3.5	3.1/4.5	4.2/5.9	4.9/6.8	5.5/7.4	5.7/7.4	4.9/6.4	3.3/5.6	2.9/4.4	1.9/2.8	1.6/2.2	4.1/4.7
Latitude -15	Average	3.4	4.0	4.7	5.5	5.9	6.3	6.5	6.1	5.3	4.6	3.4	2.9	4.9
	Min/Max	2.4/4.2	3.1/4.9	3.5/5.4	4.4/6.5	4.9/6.8	5.4/7.3	5.6/7.4	5.1/6.9	3.6/6.6	3.6/6.0	2.5/4.3	2.2/3.7	4.6/5.4
Latitude	Average	3.8	4.3	4.8	5.4	5.6	5.8	6.0	5.9	5.4	5.0	3.8	3.3	4.9
	Min/Max	2.7/4.8	3.3/5.4	3.5/5.7	4.2/6.4	4.6/6.4	4.9/6.6	5.2/6.8	4.8/6.6	3.5/6.8	3.8/6.6	2.7/4.9	2.5/4.3	4.5/5.5
Latitude +15	Average	4.1	4.4	4.7	5.0	4.9	5.0	5.3	5.3	5.2	5.0	4.0	3.5	4.7
	Min/Max	2.8/5.2	3.3/5.6	3.3/5.6	3.9/5.9	4.1/5.7	4.3/5.7	4.5/5.9	4.4/6.0	3.3/6.5	3.8/6.7	2.8/5.3	2.6/4.7	4.3/5.3
90	Average	3.8	3.8	3.5	3.1	2.7	2.5	2.7	3.1	3.6	4.0	3.5	3.3	3.3
	Min/Max	2.5/4.9	2.7/4.8	2.4/4.2	2.5/3.6	2.3/2.9	2.3/2.7	2.4/2.9	2.6/3.5	2.3/4.5	3.0/5.5	2.4/4.8	2.3/4.5	2.9/3.7

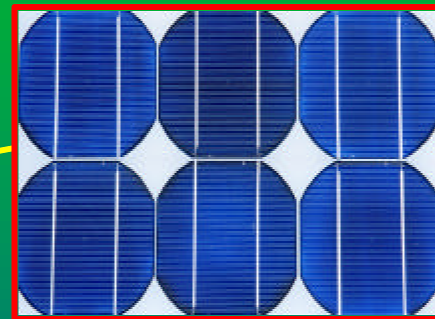
Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis (kWh/m²/day), Uncertainty ±9%

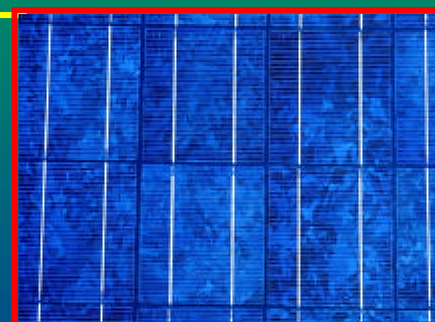
Axis Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.3	4.2	5.3	6.7	7.7	8.4	8.7	7.8	6.4	5.1	3.4	2.7	5.8
	Min/Max	2.3/4.1	3.2/5.2	3.8/6.5	5.0/8.4	6.1/9.2	6.8/10.2	7.2/10.3	6.1/8.9	4.0/8.2	3.9/6.8	2.5/4.4	2.1/3.5	5.3/6.6
Latitude -15	Average	4.1	4.9	5.9	7.1	7.8	8.4	8.8	8.1	6.9	5.9	4.1	3.5	6.3
	Min/Max	2.8/5.3	3.7/6.2	4.1/7.3	5.2/8.8	6.1/9.4	6.8/10.1	7.3/10.4	6.3/9.3	4.2/9.0	4.4/8.0	3.0/5.5	2.5/4.6	5.8/7.2
[illegible]	Average	4.5	5.2	6.0	7.0	7.5	8.1	8.5	8.0	7.0	6.2	4.5	3.8	6.4

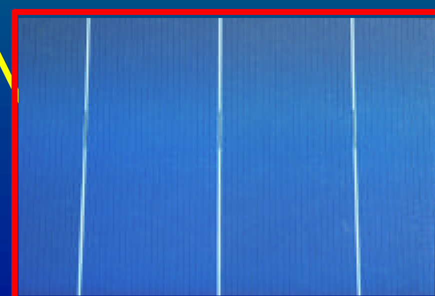
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Record Maximum Temp	20.6	24.4	30.0	33.9	33.3	40.6	41.7	42.8	38.9	33.3	27.8	21.1	42.8
HDD, Base 18.3°C	677	526	384	181	75	4	0	3	31	155	365	596	2996
CDD, Base 18.3°C	0	0	0	6	59	141	233	194	73	10	0	0	716
Relative Humidity (%)	68	67	64	61	66	68	66	68	70	64	68	71	67
Wind Speed (m/s)	4.9	4.9	5.5	5.4	4.6	4.3	4.1	4.0	4.1	4.5	4.8	4.8	4.6

Photovoltaic Modules:
to Generate DC Electricity

- Flat plate types
  - Crystalline silicon
    - Single-crystal
    - Polycrystalline
  - Amorphous silicon
  - Cadmium-tellurium
  - Copper-indium-diselenide
- Concentrator types
  - Low, medium, high concentration

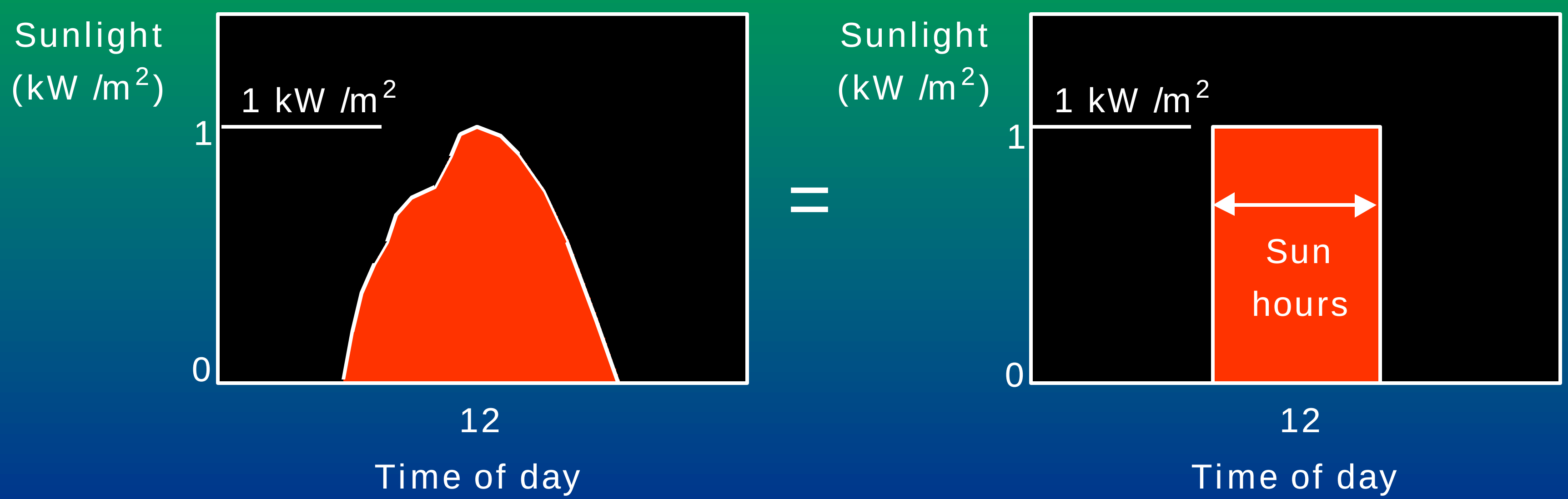






Module “Rated Power”

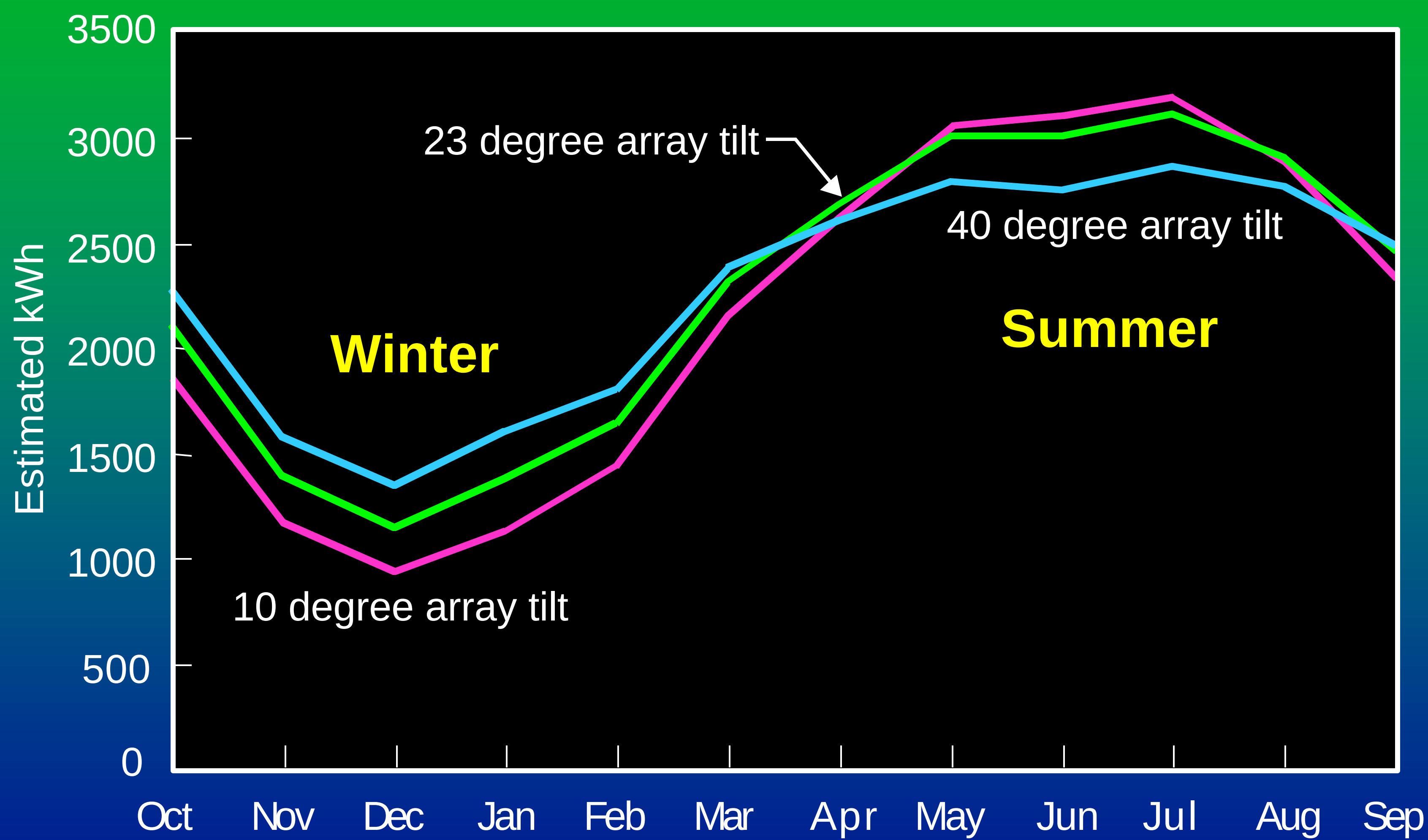
Module “Rated Power” is the output of a PV module under standard rating conditions (1 kW/m^2 light, 25°C cell temperature, 1 m/s wind speed).



Example: 3.6 kWh/m^2/day = 3.6 “sun hours”/day at 1 kW/m^2

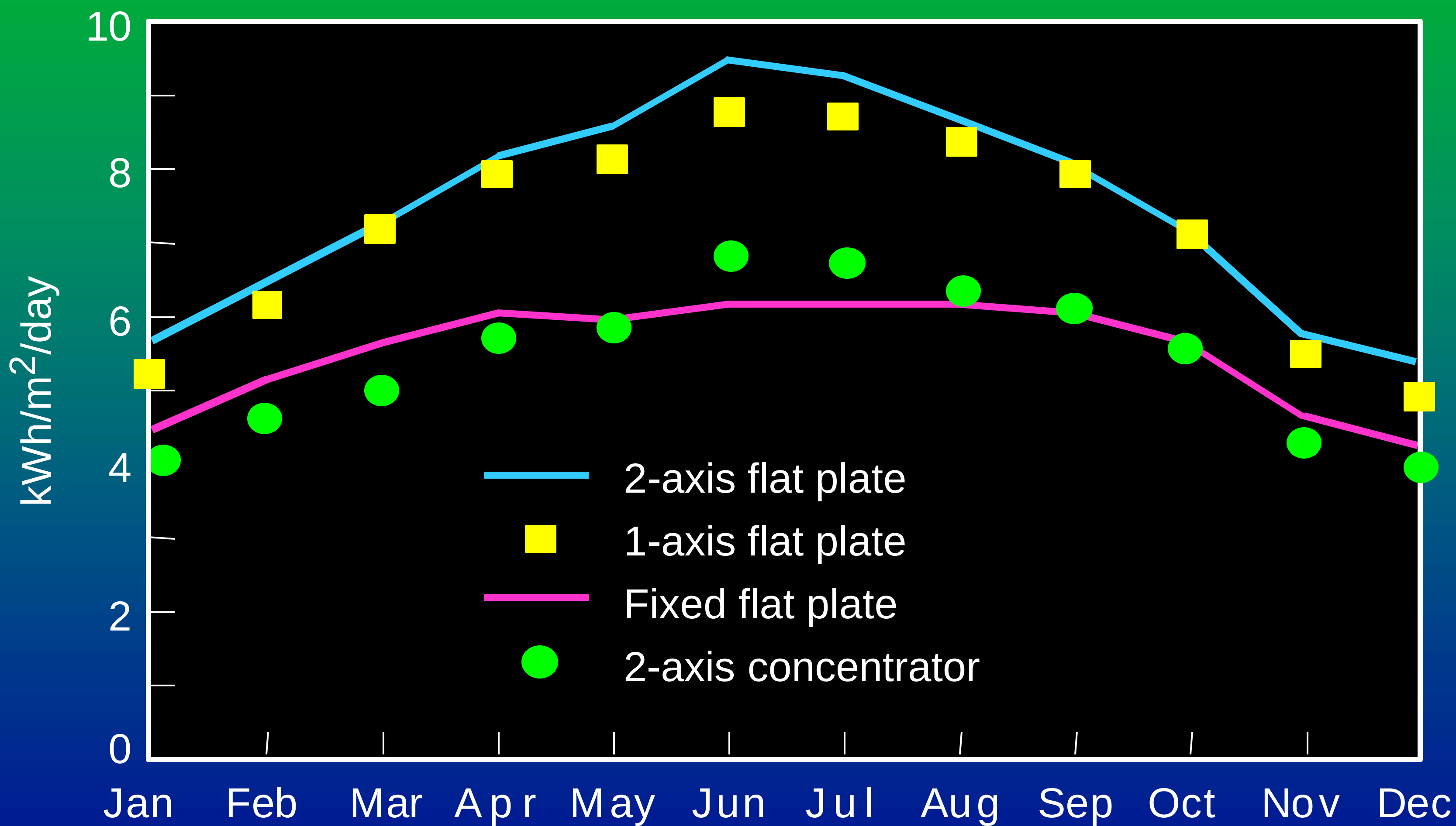
A module “rated” at 50 W would produce 180 Wh in that day.

Effect of Tilt for Fixed Flat Plate



Tracking versus Fixed

Average Daily Solar Resource in Boulder, Colorado




Custom heavy duty
metal support structure


PowerGuard
systems from
PowerLight


UniSolar's metal standing
seam roofing system

Ascension's roofjack mounting system - no roof penetrations

Rough Estimate of Required PV Power
(for an AC grid-connected system)

- Take the daily average load in kWh/day.
- Divide the daily average load by the average number of “sun hours” to get the required PV power.
- Multiply the PV power by 1.3 to account for system losses.
- This is a rough estimate of the PV system size in kilowatts (kW_{dc}).
- More exact sizing programs and publications are available.

Three Systems Examples

Off-Grid Irrigation System with PV System

- City parks in Littleton, Colorado
- LEIT 8000 Irrigation Management System with built-in PV power supply
- Installed cost of PV powered systems ranged from $1442 to $2181
- In 3 out of 4 parks the PV powered system was similar in cost or cheaper than a buried utility line extension

Comparative Cost of Irrigation Controllers

Four Park Projects in Littleton, Colorado

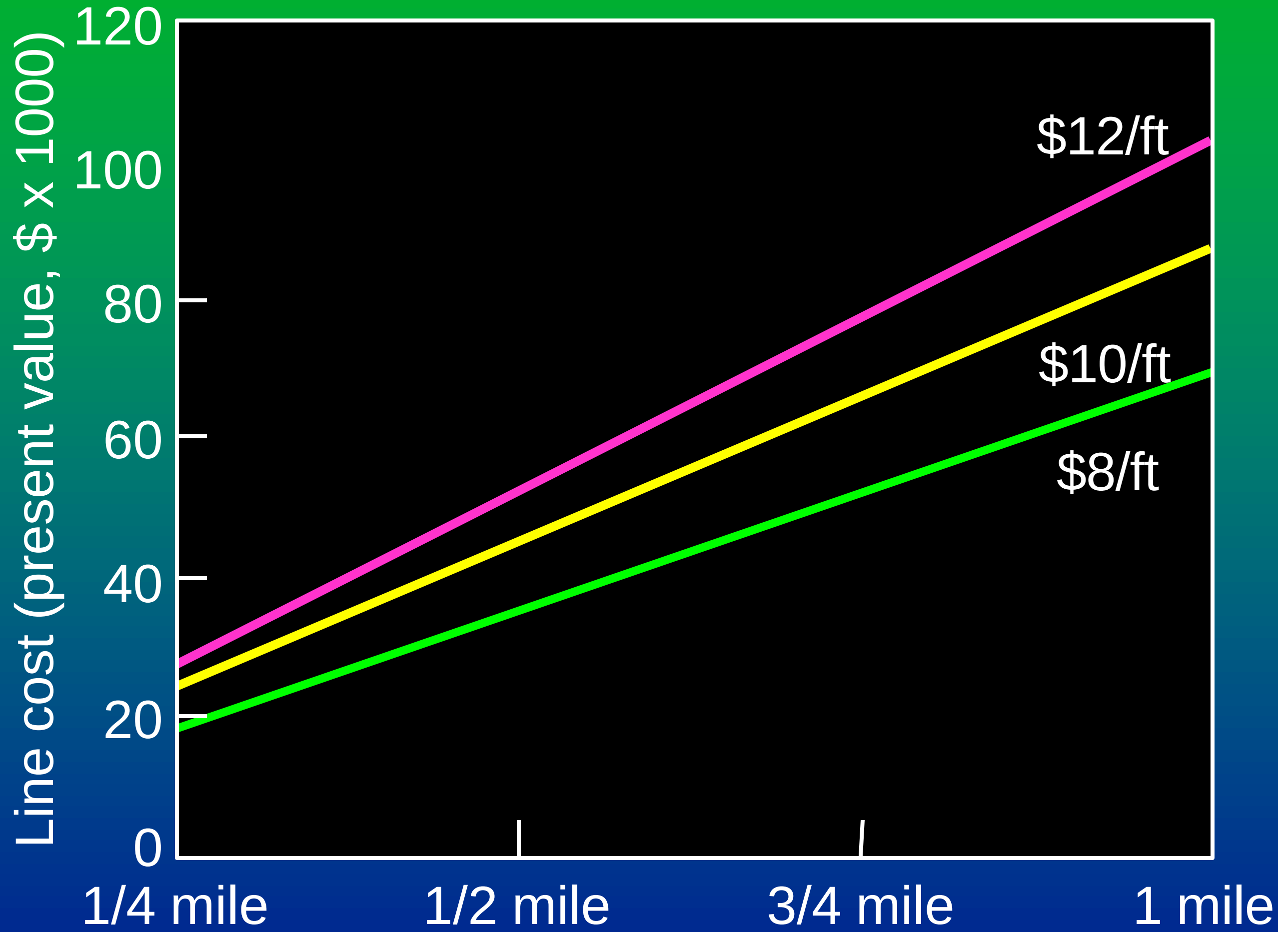
Park No.	Total Installed Cost of PV System	Total Installed Cost of Utility System†	Cost of Irrigation Equipment	Cost of Utility Intercon-nection
1	1442	1323	598	725
2	2108	1402	677	725
3	2181	2177	677	1500*
4	2181	5477	677	4800**

† does not include monthly service charges

* includes $600 for trenching in soil

** includes $600 for trenching in soil and $3300 for street cut and patch

Costs for Line Extensions



Source: PG&E

Grid-Connected PV System on FERC Headquarters, Washington, DC

- 2.4 kW_{dc} system; 3600 kWh_{ac} per year
- \$13/W installed, sole source procurement, tight schedule
- Dedicated January 18, 2001

FERC HQ Installation Considerations

- Utility has network protectors at the building service entrance to prevent reverse power onto the utility network.
- FERC wanted a rooftop installation with no roof penetrations.
- The building is not in a residential or historic district - no special permits were required.
- The 11-story building is privately owned, operated by a management company, and leased by the GSA.

Off-Grid PV System at Pinnacles National Monument

- 9.6 kW PV system with 20 kW propane generator.
- Hybrid PV system replaced 2 older diesel generators
- Total system cost was $150,000.
- Discounted payback occurs in year 6.

Pinnacles National Monument Installation Considerations

- Previously, electricity was provided by diesel generators. Risk of a spill during fuel transportation and engine maintenance costs were a concern.
- Conservation and energy efficiency measures were required.
- Batteries need to be replaced about once every 8 years at a cost of $22,000.

Procure the System

- Prepare bid specifications
  - Performance based specifications are preferred over narrow equipment specific specifications.
  - Be clear on vendor's and buyer's responsibilities.
- Solicit bids
  - Competitive
  - GSA Listing
  - Sole Source
  - ESPC

What to Look for in a PV System

- Does the system meet your needs?
- Are there good components (UL, etc.)?
- Are the components appropriately sized?
- Any warranties or maintenance agreements?
- What is the required maintenance and cost?
- Who will be responsible for maintenance?
- Is the National Electrical Code followed?

How Much Will the PV System Cost?

- A rough cost estimate for an installed grid-interconnected PV system is $10 per watt of installed PV modules. PV systems with batteries will be slightly higher.
- For example: A 2000 W_{dc} PV system is about $20,000.

How Much Will the PV System Cost?

- The *BEST* cost estimate for a PV system is a vendor's quote. The estimate can vary depending on location, installation and interface requirements, schedule, equipment availability, size and energy storage capacity.
- The *LOWEST* price is usually obtained through competitive procurements.

Install the System

- Permits and authorizations should be obtained before installation begins.
- Typical system installation times are 1-3 days on site, depending on system size and complexity.
- Installation must meet all building, zoning, and National Electric Codes.
- A facilities manager should be present during installation.
- The installation should be done in accordance with the building owner's or operator's policies and procedures - the same as any other on-site contractor.

Commission the System

- Perform tests, evaluations and inspections to verify that the system meets the procurement specifications.
- Plan a ceremony, invite your boss, cut the ribbon, throw the switch and watch the meter run backwards.

Maintain System and Monitor the Performance

- Perform vendor recommended maintenance on the system.
- Have a visible indicator (meter, display, light) that shows if the system is working.
- Monitor system performance to verify how well the system is working.
- Have a public display of the system output and an informative description of the system and benefits.

Maintenance Issues

- PV systems are low maintenance - but are not “no maintenance.”
- Make maintenance part of someone’s job description.
- Follow vendor’s recommended maintenance schedules to maintain warranties.

Frequently Encountered Problems

Fatal Error #1	Ignore or don't coordinate with electric utility or local building inspectors
Fatal Error #2	Overestimate solar resource
Fatal Error #3	Underestimate loads or energy needs
Fatal Error #4	Undersize the PV or batteries to trim costs
Fatal Error #5	Nobody is responsible for well-being of project and equipment

Suggestions for Success

- Identify expectations clearly
- Accurately define the project requirements
- Identify a champion within the agency to pursue the project
- Select a qualified vendor and use proven products
- Meet ongoing maintenance requirements


047
You can do it!